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Computed tomography image analysis for Indonesian total hip arthroplasty designs

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ABSTRACT

Total hip arthroplasty purposes to replace a hip joint damaged by an artificial hip joint. However, the developed products that already exist in the market lead to the mismatch between the hip implant equipment and the patient's bone morphometric. Besides causing complications, the mismatch also continues to the dislocation effects, fracture, osteolysis, and thigh pain. This paper aims to design a customized hip implant based on real patient data, particularly for Indonesian patient, limited to the acetabular components and stem parts. The computed images were analyzed to estimate the patient proximal femur morphometric; those are the femoral head diameter, neck-shaft angle, mediolateral width, anteroposterior width, neck length and neck width. The experiment has succeeded in designing the acetabular shell with the thickness of 3 mm, the acetabular liner with the thickness of 6 mm, the femoral head between 22.4 to 24.8 mm, the short stem in both the right for 110.656 mm and left femur bone for 111.49 mm; that fit the patient's femur bone. Overall, the proposed steps in designing the customized hip implant in this work, based on image analysis on medical imaging data, can be a standard to be applied for other patient-needs hip arthroplasty implants.

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1. INTRODUCTION

Total hip arthroplasty (THA) is an orthopaedical surgery procedure to replace the acetabulum cartilage with an artificial metal shell. The head and neck of the femur are replaced by a prosthesis in the form of a rod and a ball made of metal [1]. It is one of the most cost-effective operations and the most successful operation compared to surgeries in other orthopedic fields [2]. The hip implants mainly consist of two components: acetabular components and femoral stem. The first reported hip implant was generated by Philip Wiles in 1938 using a metal-on-metal bearing [3]. Based on research by McKee, the hip implant using a metal-on-metal approach faced problems of loosening and subsequent mechanical failure [3]. Investigations about finding the most effective hip implant design and materials have always been conducted to manage the issues. The study of the femoral stem is vital to appraise clinical success due to its compatibility within the proximal femur [4]. Nowadays, there is a wide range of hip implant designs differing in geometric features and configurations to closely mimic a patient's hip geometry [5], [6]. On the latest cutting-edge implant design technology, computed tomography scanning (CT-Scan) or magnetic resonance imaging (MRI) images are used to define the best measurement for implant design, including hip and knee [7], [8]. Particularly in the Indonesian case, a previous study has succeeded measuring the three-dimensional (3D) morphometry of proximal femur to design the best-fit femoral stem for the Indonesian population [9]. However, in that work, it only focused on giving the proposed dimension of proximal femur component with no hip implant design result for the Indonesian data.

THA offers new hope for the osteoarthritis (OA) patient, in particular for the recovery process, the functional restoration, quality of life improvement in a better condition [10]. As the main cause of joint movement disorders, OA has affected more than 30 million people in the United States (US) and about 41 of a thousand people per year in the United Kingdom (UK) [11]. In 2018, Indonesia had a 7.3% prevalence rate of joint disease, continuing to increase. OA is the most common joint disease in Indonesia [12]. The high number of OA sufferers worldwide causes a substantial increase in THA procedures. A lot of health companies manufacture hip prostheses to meet the needs of THA in global demand. THA is also used for people who suffer from a fracture of the neck femur, congenital abnormalities, tumor, joint damage, and other hip joint diseases [13]. However, the companies that produce the hip prosthesis of hip implants currently only use the proximal femur parameter of western society to reference the dimensions [9]. According to the world population review (WPR), the countries that are included in the western community category (WCC) are countries in the continent of Europe, America, and Australia [14]. Research reveals that the size of the proximal femur in Indonesian society is smaller than in western civilization after conducting a comparison experiment of the proximal femur size using multinational data [9]. Femoral morphology and size are different between men and women [15]. Because there is a variation of femur proximal measures, not all hip implants in the market are suitable with bone morphometry. If the size of the applied hip prosthesis or the hip implant does not match the patient's body morphometry, it will cause discomfort to the patient. The mismatch between the hip implant and bone morphometry leads to dislocation, fracture, osteolysis, and other complications. Therefore, composing the THA design that is adapted to bone morphometry is essential.

This work aims to design a customized hip implant based on femoral proximal Indonesian female morphometry measurement using the latest correlated literacy [9]. In 2019, Tuong [16] summarized from several previous works that femur geometrical parameters of the Vietnamese population are different from Asian people, those are Thai, Malay, Indian, and Japanese. All those works employed very complex methods from generating medical imaging data, creating it into 3D models of the femur bone, measuring the femur geometrical parameters, designing the implant, and finding it very time-consuming. Besides that, the image processing steps in the reverse engineering of femur bone may be leaving inaccuracies. The 3D reconstruction of femur bone can be replaced using multiplanar reconstruction to simplify the process, and it is more accurate for measuring the bone morphometry [17]. Furthermore, the literacy of patient-specific hip implant design for Indonesian people, particularly for women, is very limited. The plan will significantly contribute to the scientific recommendation regarding the implant design in the most suitable THA based on bone morphometry of the Indonesian people.

2. RESEARCH METHOD

The research method consists of two main stages: data acquisition and parameters measurement. The data was acquired from a CT-Scan 128 slice dual source belonging to the Cipto Mangunkusumo Hospital Jakarta with the permission of the radiologist and the orthopedist. The equipment can perform organ reconstruction in 3D with a very short examination time and provides a high-resolution picture. The data is a type of CT pelvis or lower abdomen. It consists of 374 images loaded in the multiplanar reconstruction feature in Radiant Dicom with a free 30-days trial. The patient is female, has a weight of 61 kg, a height of 165 cm, and 49 years old. In this work, we apply five parameters that are used for designing the hip implant; those are femoral head diameter (FHD), mediolateral width (MLW), anteroposterior width (APW), neck shaft angle (NSA), neck length (NL), and neck width (NW). Figure 1 shows the FHD measurement. FHD is measured from the edge of the femoral head bone to another edge [18]. The MLW and APW are calculated on an axial plane horizontally and vertically and consist of 3 types. Figure 2 shows the three types are 20 mm above the lesser trochanter, 20 mm below the lesser trochanter, and 40 mm below the lesser trochanter. Figure 3 exhibits the APW and MLW for all three types in the right and left femurs [9]. APW1 and MLW1 for right femur are in Figure 3(a) and left femur are in Figure 3(b). APW2 and MLW2 for right femur are in Figure 3(c) and left femur are in Figure 3(d). APW3 and MLW3 for right femur are in Figure 3(e) and left femur are in Figure 3(f). NSA is the angle between the femoral head and passing through the shaft. NL is the length between the femoral head center and the femoral axis. NW is the width of the femoral neck measured horizontally. The neck width is also measured to estimate the acetabular head. Figures 4 displays the NSA in Figure 4(a), NL, and NW measurements in Figure 4(b) [18]. Parameter measurement results will be discussed as the main considerations for designing the implants. In this study, we used Autodesk Inventor Professional.

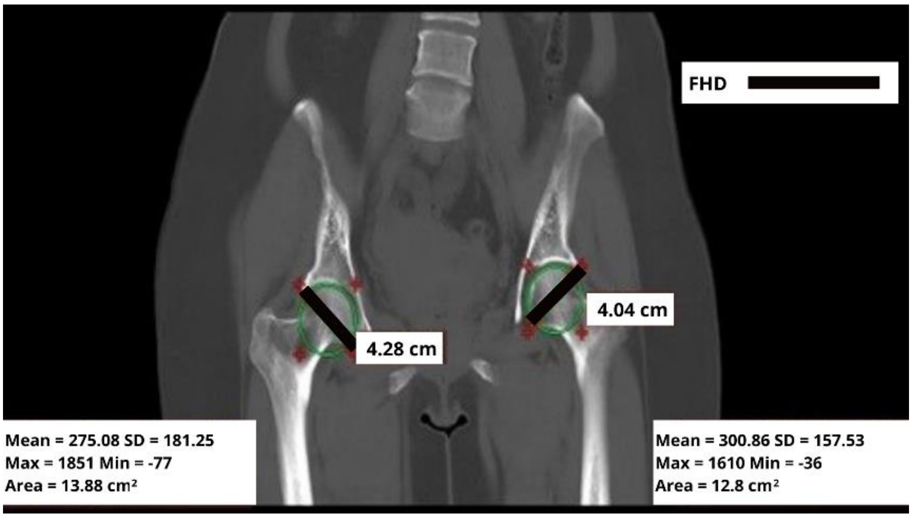


Figure 1. FHD measurement

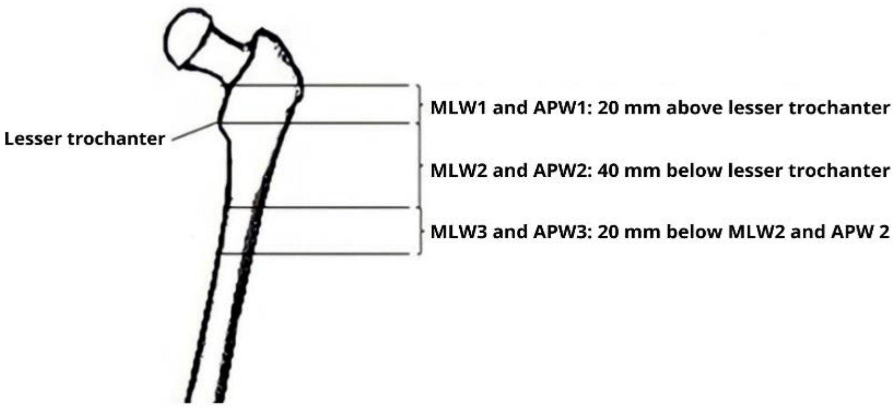


Figure 2. MLW and APW measurements

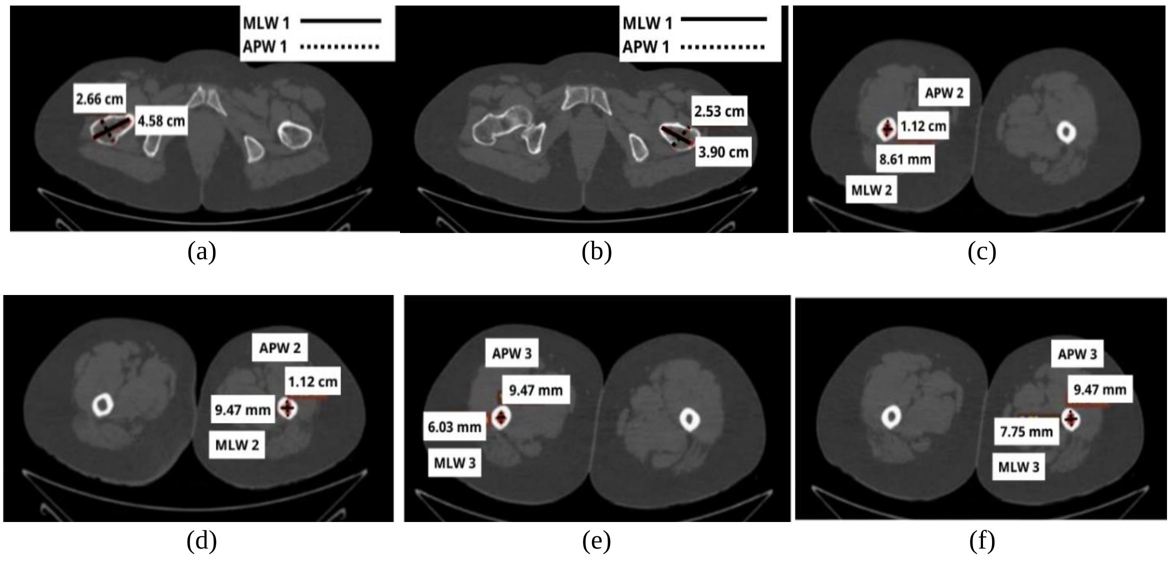
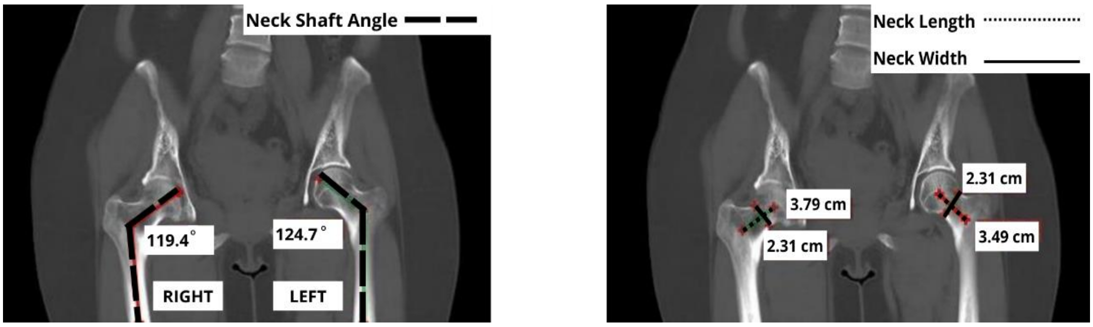


Figure 3. MLW1 and APW1 measurement on the (a) right femur and (b) left femur, MLW2 and APW2 measurement on the (c) right femur and (d) left femur, and MLW3 and APW3 measurement on the (e) right femur and (f) left femur



(a) (b)

Figure 4. Measurement on the right and left femur for the (a) NSA and (b) NL and NW

3. RESULTS AND DISCUSSION

According to the measurement results in this study as seen in Table 1, compared to several measurements in other different ethnic groups, as shown in Table 2, the Indonesian data has several smaller numbers of the proximal femur in almost available parameter measurements than Indian, Swiss, France, Thai, and American [19]–[23]. The femur proximal measurement results will be fundamental to design the acetabular components and stem. The most appropriate size for the design of acetabular components is following the patient's femoral head diameter [19].

Table 1. The measurement of Indonesian woman's proximal femur

Variable	Right	Left	Mean
Femoral head diameter	42.8 mm	40.4 mm	41.6 mm
Mediolateral Width 1	43.0 mm	40.0 mm	41.5 mm
Mediolateral Width 2	11.0 mm	11.0 mm	11.0 mm
Mediolateral Width 3	7.0 mm	9.6 mm	8.3 mm
Anterioposterior Width 1	26.6 mm	25.3 mm	25.95 mm
Anteroposterior Width 2	11.2 mm	11.2 mm	11.2 mm
Anteroposterior Width 3	9.47 mm	9.47 mm	9.47 mm
Neck Shaft Angle	119.4°	124.7°	122.05°
Neck Length	37.9 mm	34.9 mm	34.6 mm
Neck Width	23.1 mm	23.1 mm	23.1 mm

Table 2. Comparison of proximal femur measurement reported in different studies (n= number of specimens)

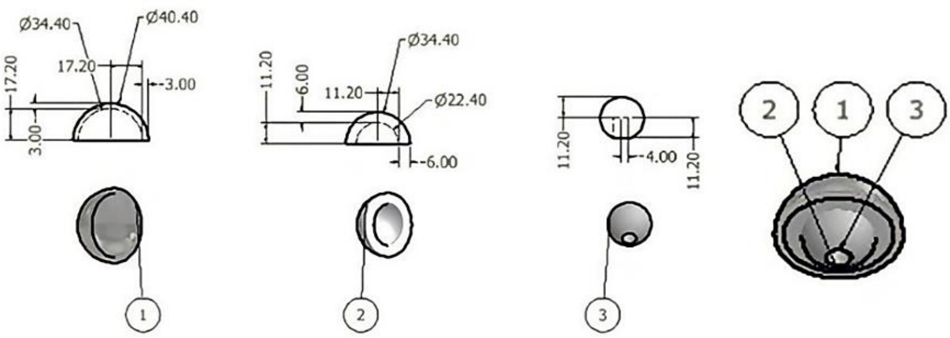
Parameter	Indonesian (n=2)	Indian [20] (n=400 and 98) Mean+SD	Swiss [21] (n=32) Mean+SD	Western [22] (n=75) Mean+SD	Thai [23] (n=240) Mean+SD	American [24] (n=120) Mean+SD
Femoral head diameter (mm)	41.6	41.0□2.70	46.29+4.02	45.53+3.40	43.1+3.44	45.88+3.61
Neck Shaft Angle (°)	122.05	132.62+5.50	126.35+4.29	123.65+4.29	127.45+5.00	122.52± 3.09
Neck Length/Width (mm)	34.6/23.1	28.59+2.92	-	-	44.91+3.94	25.21□4.76

Table 3 shows the calculation for acetabular components [25], [26]. The thickness of 3 mm will be very suitable for acetabular shell because it has higher stiffness than the 4 mm thickness [25]. A thickness of 6 mm was applied for the acetabular liner based on the recommendation to prevent the fracture [26]. In this study, the size of the femoral head is in the classification of the small femoral head size, which is not less than 22 mm and does not exceed 28 mm [27]. Figure 5 shows the left acetabular components configuration in Figure 5(a) and the right one in Figure 5(b), whereby 1 and 3 are acetabular shell and femoral head with metal and 2 is acetabular liner with polymer. Compared with the previous studies, when the acetabular component exceeds the size of the patient's femoral head, it may lead to fracture [13]. Dislocation may occur if the acetabular component is smaller than the size of the patient's femoral head. The acetabular components design has been adjusted to the femoral head patient's morphometry.

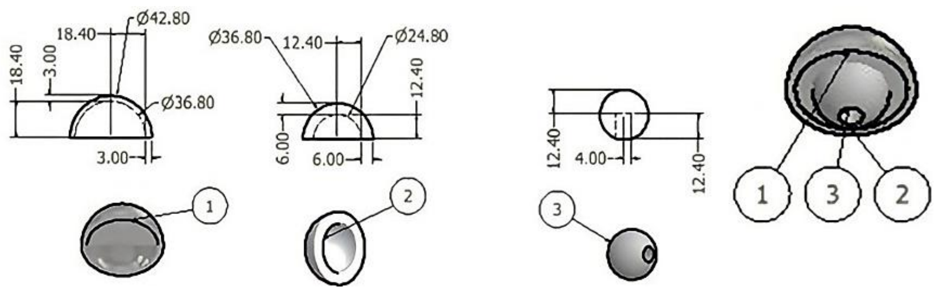
FHD, MLW, APW, and NSA are the main considerations in stem design [18]. Table 4 shows all estimations in the femoral stem design. Figure 6 for the left femur and Figure 7 for the right femur illustrate detailed dimensions and points to assist the design estimation. The NSA and NL are functioning to estimate and reduce the area's torque during the load cycle [4]. The femoral stem width varies depending on the mediolateral width size [28]. Estimation of the slope angle between the stem and the neck on the femoral stem is considered by measuring the NSA [4]. The femoral stem's NL is considered by calculating the femur bone's NL [4]. A femoral stem's length can be categorized into two types, a conventional stem with more than 120 mm and short stem with less than 120 mm [29], [30]. Those two studies conclude that the short stem has more clinical success and provides reliable long-term results. The risk of intraoperative fracture and stem loosening tends to be smaller than other types [31]. The short stem does not require a lot of bone to be drilled so that the remaining available bone will provide an opportunity for further revision surgery [29]. In this work, the stem length (point A to point I in Figures 6 and 7) is drawn less than 12 cm and has been justifying the bone patient's morphometry. The femoral stem length in this work is comprised of the line from A-I-J-K-I. The letter A is a point where the line of intersection between the y-axis and the NSA.

Table 3. The calculation for acetabular components

Component	Right	Left	Notes
Acetabular Shell	$D_{AS} = D_L - \Delta x_{AS}$	$D_{AS} = D_L - \Delta x_{AS}$	D_{AS}=Inside diameter of acetabular shell
	$D_{AS} = 42{,}8 - (3 + 3)$	$D_{AS} = 40{,}4 - (3 + 3)$	D_L=Outside diameter of acetabular shell
	$D_{AS} = 42{,}8 - 6$	$D_{AS} = 40{,}4 - 6$	$\Delta x = X_1 + X_2$
	$D_{AS} = 36{,}8$	$D_{AS} = 34{,}4$	X=Thickness
Acetabular Liner	$D_{AL} = D_{AS} - \Delta x_{AL}$	$D_{AL} = D_{AS} - \Delta x_{AL}$	AS= Acetabular shell
	$D_{AL} = 36{,}8 - (6 + 6)$	$D_{AL} = 34{,}4 - (6 + 6)$	AL=Acetabular liner
	$D_{AL} = 36{,}8 - 12$	$D_{AL} = 34{,}4 - 12$	D_{AL}=Inside diameter of acetabular liner
	$D_{AL} = 24{,}8$	$D_{AL} = 22{,}4$	FH=Femoral head
Femoral Head	$D_{FH} = D_L - (\Delta x_{AS} + \Delta x_{AL})$	$D_{FH} = D_L - (\Delta x_{AS} + \Delta x_{AL})$	D_{FH}=Inside diameter of femoral head
	$D_{FH} = 42{,}8 - (6 + 12)$	$D_{FH} = 40{,}4 - (6 + 12)$	
	$D_{FH} = 42{,}8 - 18$	$D_{FH} = 40{,}4 - 18$	
	$D_{FH} = 24{,}8$	$D_{FH} = 22{,}4$	



(a)



(b)

Figure 5. Design of acetabular components for (a) left femur and (b) right femur. 1, 2, and 3 indicate acetabular shell, acetabular liner, and femoral head

The lesser trochanter is located in the H letter. The MLW1 is 20 mm above parallel to the H letter. The MLW 2 is 40 mm below the lesser trochanter. The distance of I to J will be a representative distance between MLW1 and MLW2. The MLW3 is 20 mm below the MLW2. The distance of J-K is a concept of distance between MLW2 and MLW3. In the APW parameter, the minimum number that has been obtained is 9.47 mm. The APW has the main attention to estimating the femoral stem thickness. The femoral stem cannot properly fit into the bone cavity if the femoral stem thickness is greater than the minimum size of APW [18]. Here, we apply a thickness of 8 mm to allow the stem to enter the bone. Rawal *et al.* [18] have been proposed the dimension of the femoral stem for the Indian population. If we look at the proposed extent of the Indian women population, Indian has slightly higher numbers in all proximal femur morphometry parameters. The proposed dimension was three types of stem lengths: 120 mm, 125 mm, and 130 mm [18]. Compared with our design, in which the size stems are 110.656 mm for the right implant and 111.49 mm for the left implant, our plan has a shorter dimension than the Indian. Based on the created hip implant design, the design is close to the patient's proximal femur morphometry. As the first literacy to design the THA based on the real patient's CT, particularly in the Indonesian race, this paper expects being a main reference in the patient-specific or customized hip implant design based on medical images such as CT-scan and magnetic resonance imaging (MRI). Since we intend to understand the need for a special patient that will not match general commercial hip implants, the measured data in this study is limited to only one case. The number of specimens should be increased to have a more comprehensive study in a specific clan.

Table 4. Femoral stem design estimation

Variable	Right	Left	Determination
H-B (mm)	43	40	Based on MLW 1 parameter measurement
G-C (mm)	11	11	Based on MLW 2 parameter measurement
F-D (mm)	7	9.6	Based on MLW 3 parameter measurement
I-J (mm)	60	60	The distance between MLW 1 and MLW 2
J-K (mm)	20	20	The distance between MLW 2 and MLW 3
K-E (mm)	20	20	The distance between MLW 3 and the edge of femoral stem
A-E (mm)	110.656	111.49	Femoral stem length
I-L (mm)	37.9	34.9	Based on Neck Length parameter measurement
< LIE (°)	119.4	124.7	Based on Neck Shaft Angle parameter measurement
Thickness (mm)	8	8	Based on minimum APW parameter: 9.47 mm. There is a 1.47 mm gap between implant and bone to provide a place for bone ingrowth

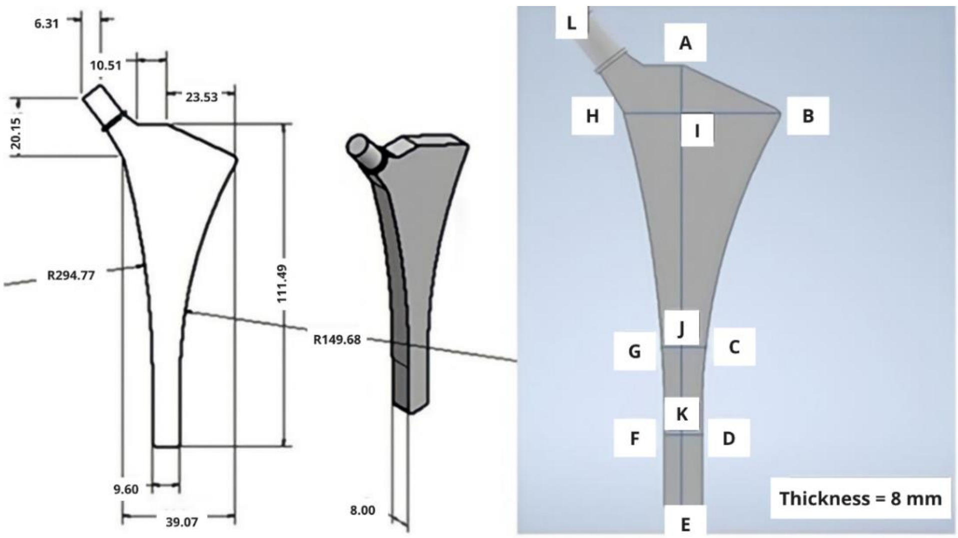


Figure 6. Stem design for the left femur consists of detailed dimensions and variables for the design estimation

In the hip implant's manufacturing process, the material selection will be the main factor in an implant application's success after a proper design. The latest trend of hip implant manufactures four types material, which are metal-on-polyethylene (MoP), metal-on-metal (MoM), ceramic-on-ceramic (CoC), and ceramic-on-polyethylene (CoP) [32]. But recently, hybrid combinations of several types were introduced [32]. There are several considerations for choosing the best material, such as implant cost, patient age, and the patient's activity level. This experiment is limited to a rough surface with a very specific dimension. Latest literacy reports that a detailed modification using uncemented, flat, and tapered stems can achieve osteointegration for distal profile [33]. The manufacture of the optimal THA design, adapted to the biocompatible material, will allow the clinical trial, such as preliminary investigation on the cadaver. Using a patient need dimension for the THA components combined with the latest trends for both acetabular and stem will complete the THA study.

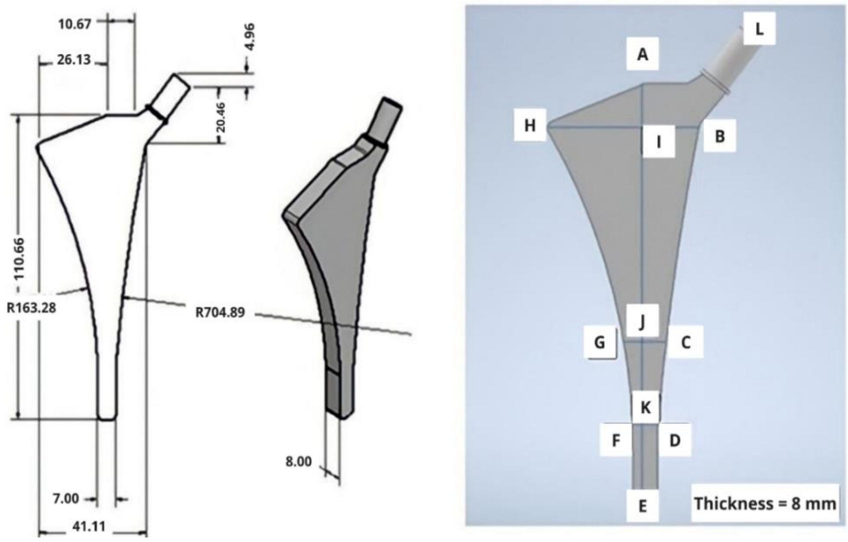


Figure 7. Stem design for the right femur consists of detailed dimensions and variables for the design estimation

4. CONCLUSION

A hip implant design has been created based on the proximal femur morphometric of the Indonesian woman patient CT data. From all measured parameters, the hip implants have been designed with these specifications: the right and left stem length of 110.656 mm and 111.49 mm; the acetabular shell with the inside diameter of 36.8 mm for right and 34.4 mm for left with each thickness of 3 mm, the acetabular liner with the inside diameter of 24.8 mm for the right and 22.4 for the left with the thickness of 6 mm, and femoral head with a diameter of 24.8 mm for right and 22.4 mm for left. The design can be a major recommendation regarding the most suitable hip implant based on the patient's bone morphometry using medical image analysis. Material selection and further modification will improve the progress after having a fitting design.

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